RAAS

Robust and Autonomous Aerobraking Strategies

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Introduction to RAAS

- **What is the RAAS Project?**
  - Research project on aerobraking, financed by ESA and carried out by DEIMOS-Space and TAS-F with following major goals:
    - Define systematically aerobraking phases and constraints
      - **Walk-In**, **Main Phase**, **Walk-Out**
    - Design GNC algorithms and operations strategies enabling aerobraking missions with a certain autonomy and robustness
      - **Autonomy of 1 week**
      - **Robustness to dust storms** without interruptions of operations and to **superior solar conjunctions** with pop-up manoeuvres
    - Validate above algorithms and strategies with dedicated tools:
      - **MAS**: **3-DOF** Mission Analysis Simulator for **long-term validation** of the orbit guidance algorithms and mission operations approach (DEIMOS-Space)
      - **Hi-FAS**: **6-DOF** High Fidelity Analysis Simulator for **short-term validation** of the attitude GNC algorithms, mode management and FDIR strategies (TAS-F)

- **Main information sources on aerobraking techniques:**
  - Literature from past aerobraking missions (Mars Global Surveyor, Mars Odyssey, Mars Reconnaissance Orbiter)

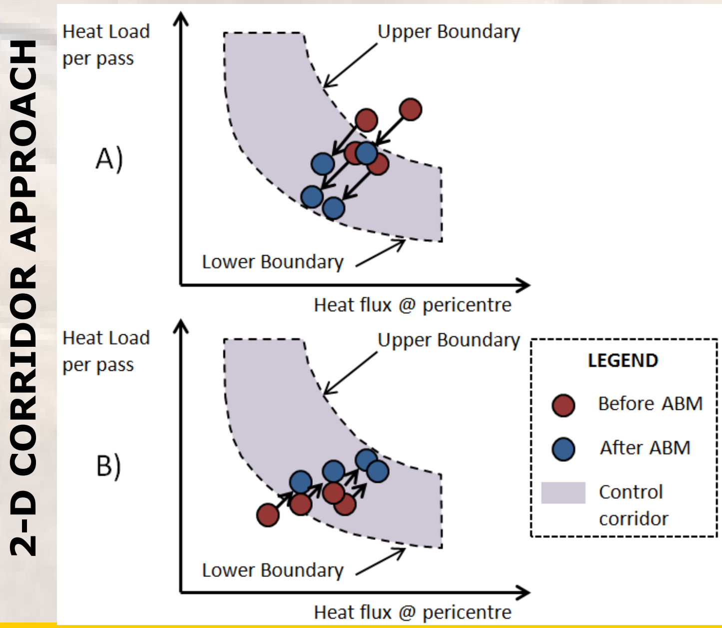
Pericentre Control: Corridor Definition

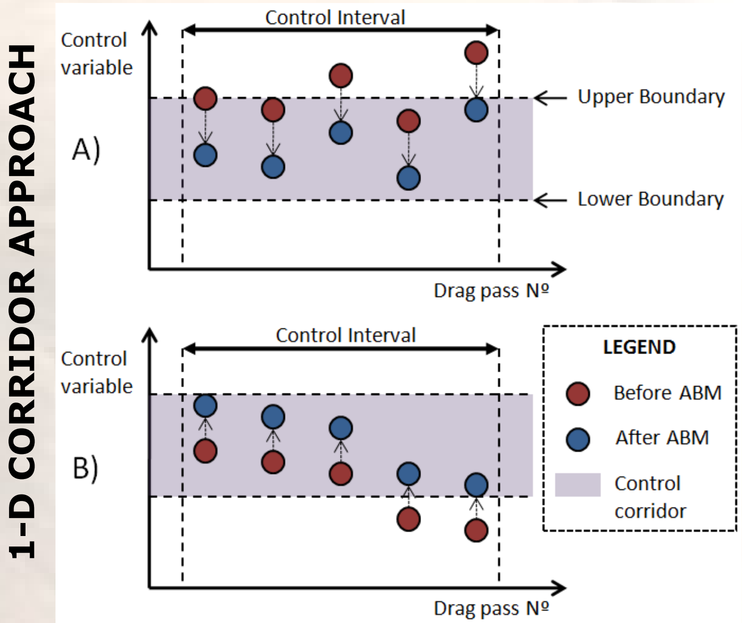
- **Past missions approach:**
  - Constant corridors of peak dynamic pressure or heat flux
  - Regular corridor updates during mission operations based on analysis of S/C thermal telemetry
    - Complex and resource demanding

- **Proposed approach:**
  - Corridor purpose:
    - **Upper Boundary** limits maximum **solar array temperature**
    - **Lower Boundary** guarantees a **minimum dynamic pressure** to achieve final orbit within a maximum amount of time
  - Drag pass duration affects greatly thermal behaviour:
    - The higher the duration, the higher the array temperature (at a given peak heat flux)
  - Proposed solution:
    - Off-line computation of corridors adapting to drag pass geometry:
      - **1-D Approach**: Allowed band of peak heat flux as a function of apocentre altitude
      - **2-D Approach**: Allowed region in peak heat flux-heat load plane

Pericentre Control: Baseline Guidance

- **Baseline Guidance Purpose:**
  - Compensate predictable orbit effects on a few days scale with ABMs at apocentre to raise/lower pericentre
- **Baseline Guidance Logic:**
  - *Baseline ABMs ensure that the predicted control variables evolution during each **control interval** fulfills as much as possible the aerobraking corridor*

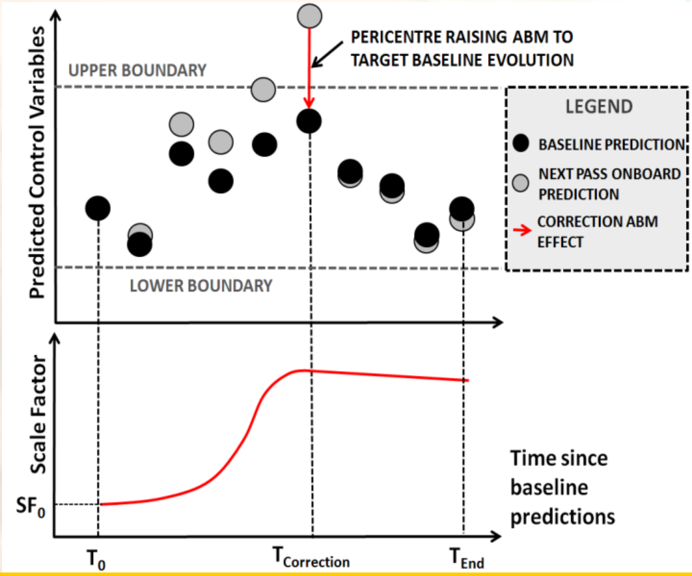




Pericentre Control: Correction Guidance

- **Correction Guidance Purpose:**
  - Compensate autonomously onboard sudden density changes at pericentre (e.g. due to dust storms) on a short term
- **Correction Guidance Logic:**
  - *Correction ABMs reproduce the baseline predicted evolution of control variables, whenever next pass onboard predicted control variables fall outside the control corridor*
- **Logical Steps:**
  - Measure peak heat flux and update scale factor for predictions (3 days moving average of measurements)
  - Predict next pass control variables with updated scale factor
  - If predictions violate corridor, compute a correction ABM to reproduce baseline heat flux value

CORRECTION ABM EFFECT

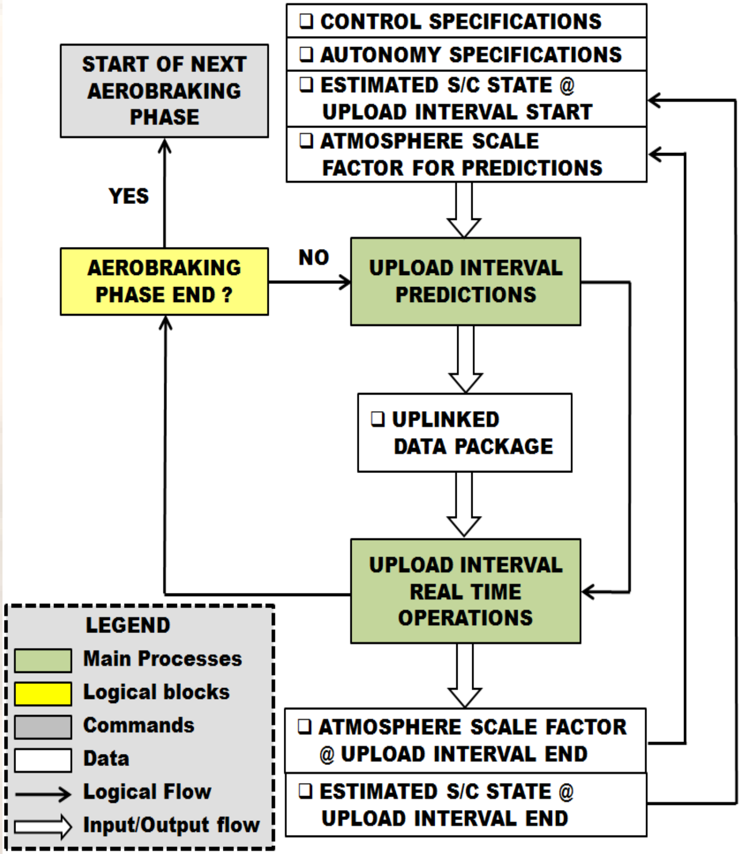


Mission Operations Approach

- **Two mission autonomy levels have been proposed:**
  - **Level 1**: Ground Baseline Guidance, Onboard Correction Guidance
  - **Level 2**: Onboard Baseline & Correction Guidance

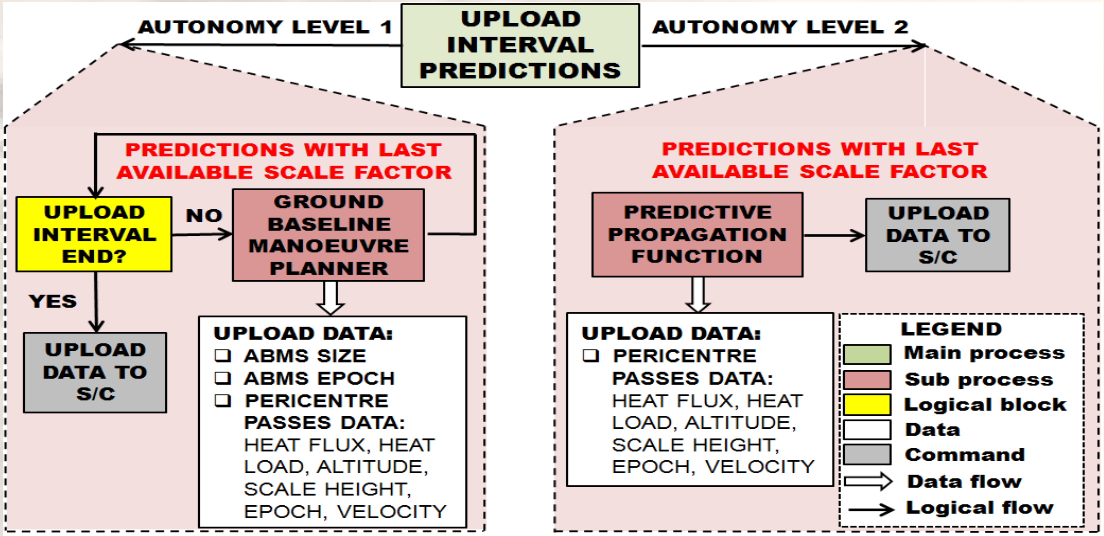
- **Mission operations feature a loop of activities per upload interval:**
  - **Upload Interval Predictions:**
    - Orbit predictions and baseline guidance (for autonomy level 1 only) to be uplinked to S/C
  - **Upload Interval Operations:**
    - Onboard algorithms execution, execution of ABMs and attitude switch manoeuvres, S/C tracking campaign

LOOP OF MISSION OPERATIONS ACTIVITIES (1 UPLOAD INTERVAL)



Upload Interval Predictions

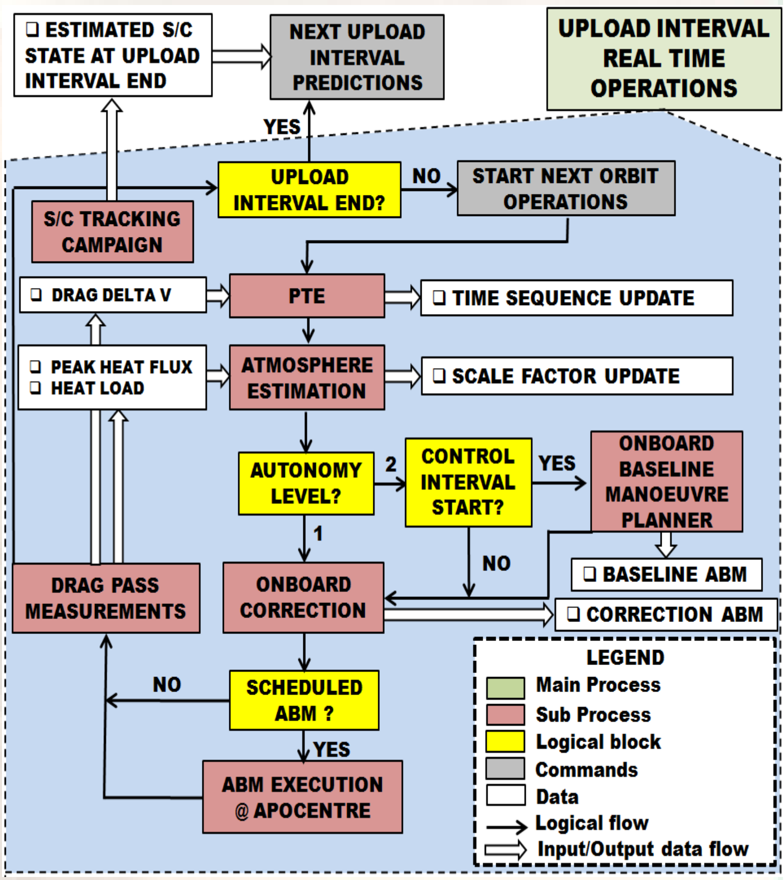
- **Upload interval predictions are required to:**
  - Build a data package to be uplinked to S/C, which contains data necessary for the autonomous execution of onboard algorithms throughout the upload interval
- **Data package contains:**
  - Baseline guidance (only for autonomy level 1)
  - Pericentre passes data (heat flux, heat load, altitude, scale height, epoch, inertial velocity) throughout upload interval



Upload Interval Real Time Operations

- **During real time operations, the following algorithms are executed every orbit:**
  - Pericentre Time Estimator
    - **Autonomous update** of in-orbit manoeuvres sequence
  - Atmosphere Estimation Function
    - Scale factor evaluation
  - Onboard Correction ABM Planner
    - Planning of correction ABMs
  - Onboard Baseline ABM Planner
    - Planning of baseline ABMs (only for autonomy level 2)
- **Terminal Activities:**
  - S/C tracking campaign to estimate state vector for next upload interval predictions

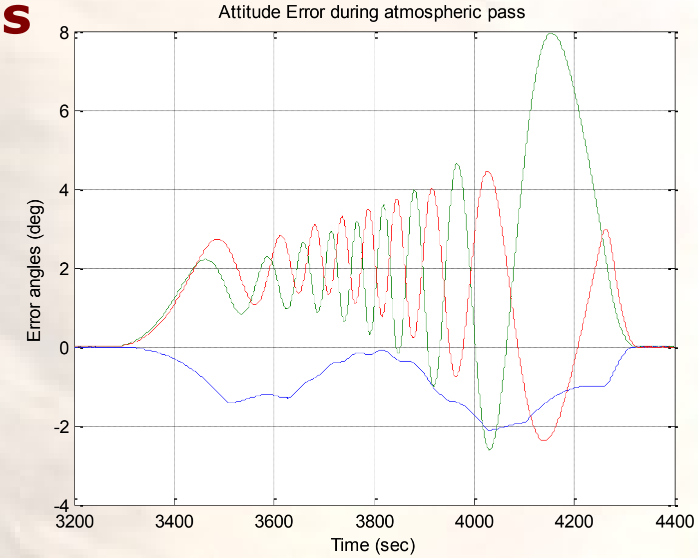
REAL TIME OPERATIONS LOOP



GNC and Attitude Control

- **Autonomous Mode Management**
  - GNC must perform several tasks within one orbit:
    - Drag pass attitude control
    - Pericentre altitude control manoeuvres at apocentre
    - Routine attitude control outside atmosphere
    - Reaction Wheels unloading
  - Autonomous Mode Management
    - Three flags (**guidance**, **navigation**, **control**)
    - It allows to switch between functions to activate

- **Attitude Control in Atmospheric Pass**
  - Stable Configuration required
  - Loose thrusters-based angular rate controller
    - Low fuel consumption
    - Use of disturbance torques to perform RWS unloading



FDIR Strategies

- **Two FDIR levels:**
  - **Safe Mode**
    - Activated in case of **Power alarm** or **Communication blackout**
    - Aerobraking not suspended
    - Autonomous detection of atmosphere through IMU measurements
    - Maximum duration of 4 days (required orbit lifetime)
  - **Automatic Pop-Up**
    - In case of **thermal alarm**, aerobraking is interrupted
    - One single manoeuvre to raise the pericentre to 150 km
    - Feasible in both **normal mode** and **safe mode**
    - Risk of mission loss:
      - Solar Arrays are the most sensitive to temperature
      - Important loss of power → loss of mission but not immediate
      - Pop-Up necessary to avoid uncontrolled re-entry (forward contamination planetary protection requirement)
  - Lower-level (consistency checks…) not defined in the frame of the study

Validation Campaign

- **RAAS validation campaign features:**
  - **Long-Term Validation**
    - Validation of mission operations design and pericentre control strategies throughout the whole aerobraking duration
    - Carried out with a **Mission Analysis Simulator** (MAS), featuring **3-DOF** dynamics integration
  - **Short-Term Validation**
    - Validation of attitude GNC algorithms, mode management and FDIR strategies
    - Carried out with a **High Fidelity Analysis Simulator** (Hi-FAS) featuring **6-DOF** dynamics integration at 10 Hz
- **Reference aerobraking scenario for validation:**
  - **Mars Sample Return – like** (aerobraking starts in Aug 2023)
    - **Initial conditions**: orbital period of 0.5 Sol, orbit inclination of 45º
    - **S/C ballistic coefficient**: 56.5 kg/m²
    - **Walk-In phase**: 2 weeks duration, 8 manoeuvres
    - **Main Phase**: 2-D Corridor, baseline ABM frequency <0.5/day
    - **Walk-Out phase**: 600 x 600 km altitude target orbit, lifetime kept above 4 days with 1 ABM per day
    - **Superior Solar Conjunction**: safe orbit at 150 km altitude

Long Term Validation Campaign

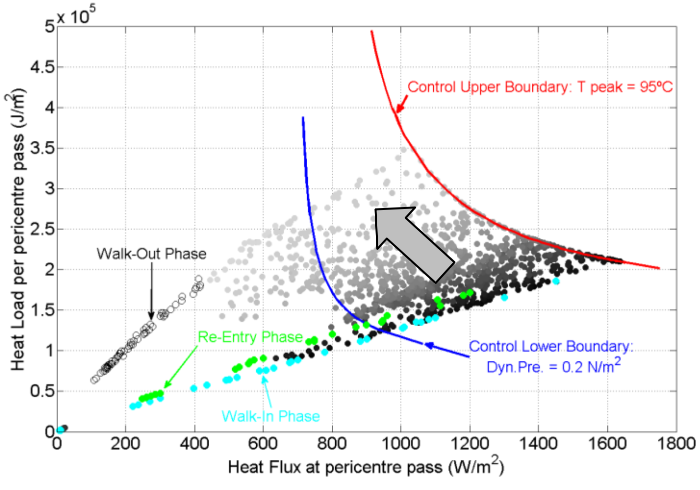
- **Three sets of scenarios were run:**
  - **Reference Scenario**:
    - Assessment of pericentre altitude guidance performance with
      - Perfect knowledge of atmosphere and orbit evolution
  - **Montecarlo Scenario**:
    - Statistical assessment of performance and robustness of proposed strategies in **real mission scenarios**, featuring:
      - Randomly perturbed atmospheres, ABM execution errors, onboard measurements errors, S/C state estimation errors etc…
  - **Worst Scenario**:
    - Assessment of robustness of proposed strategies against worst scenarios in terms of atmosphere unpredictability:
      - True orbit simulated under the LMD Dust Storm of 2001

- **Success Criteria for the tests:**
  - **AB-THERM-1:** No violation of solar array damage curve
  - **AB-ORB-1:** Orbital lifetime always above 4 days
  - **AB-OPER-1:** Overall aerobraking duration below 9 months (excluding superior solar conjunction event)

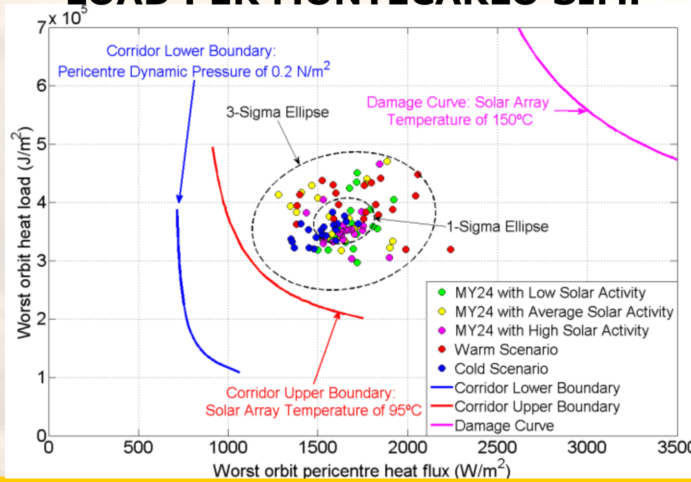
Long Term Validation Campaign: Results

- **Reference Scenario Tests:**
  - All success criteria met
  - Good overall performance:
    - Duration: 274 days
    - Cost: 148 m/s (about 100 ABMs)
- **Montecarlo Tests:**
  - All success criteria met
  - Limited dispersion in performance
  - Good PTE performance:
    - Prediction errors < 80 seconds
- **Worst Scenario Tests:**
  - AB-THERM-1 violations
  - **More conservative corridor** required for dust storm season:
    - New corridor → no violations
    - Performance deterioration:
      - 50 days (duration); 10 m/s (cost)

PERICENTRE HEAT FLUX VS HEAT LOAD FOR REFERENCE SCENARIO



WORST ORBIT HEAT FLUX-HEAT LOAD PER MONTECARLO SIM.



RAAS – Robust and Autonomous Aerobraking Strategies

Conclusions and way forward

- **The RAAS project has permitted to:**
  - Study the main factors limiting autonomy and robustness:
    - **Atmosphere prediction uncertainty**, **dust storm events**
    - **Atmosphere scale factor** for orbit predictions
  - Improve efficiency and robustness of pericentre control:
    - Two-fold guidance approach: **Baseline** plus **Correction** ABMs
  - Propose and validate new mission operations approaches
  - Propose and validate S/C attitude modes and FDIR concepts:
    - Autonomous mode management, safe mode, automatic pop-up
  - Develop new tools to validate algorithms and strategies:
    - **Mission Analysis Simulator**, **High Fidelity Analysis Simulator**

- **Future studies should aim at:**
  - Increasing the TRL of the proposed algorithms and strategies
    - Current TRL for most of technologies is **2-3**
    - Onboard algorithms require testing on **space qualified computers** and additional theoretical research to improve proof-of-concept
    - Ground algorithms and operations strategy must be tested with **real mission architectures** (ground station, real time effects…)